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A First Look at Monthly Fluctuations of Sr/Ca in *Porites* sp. from The East and West Coast of Peninsular Malaysia

(Pengamatan Pertama Fluktuasi Bulanan Sr/Ca dalam *Porites* sp. dari Pantai Timur dan Barat Semenanjung Malaysia)

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ABSTRACT

Coral cores were collected from four locations around Peninsular Malaysia and Sr/Ca ratios were measured. The interannual temperature ranges from 26.8-31.5°C. The sites chosen were Pulau Redang, Port Dickson, Pulau Tioman and Pulau Payar due to the Southeast Monsoon and Northwest Monsoon influences coupled with effects of the El Niño Southern Oscillation towards the region. Coral powder samples were sampled at 1 mm intervals along apex of extending corralites visible along the coral slab surface and analysed using ICP-OES. Ordinary least squares regression analysis showed that Sr/Ca ratios in cores from all sites have a significant negative relationship with sea surface temperature (SST). The correlation coefficients (r) were -0.704, -0.651, -0.667 and -0.600 for Pulau Payar, Port Dickson, Pulau Tioman and Pulau Redang, respectively. Values from the 2010 El Niño event were plotted against the total Sr/Ca vs SST data and decline in the regression slope was observed in the Pulau Payar core. Sr/Ca calibration using the linear least squares equation showed that the intercept (A) and slope (B) values from Pulau Tioman and Port Dickson are very similar to Sr/Ca–SST relationships generated from high resolution coral series in other studies.

Keywords: Coral; El Niño; Peninsular Malaysia; Sr/Ca; temperature

ABSTRAK

Teras karang dikumpulkan dari empat lokasi di sekitar Semenanjung Malaysia dan nisbah Sr/Ca diukur. Suhu antara tahun adalah berjulat dari 26.8-31.5°C. Lokasi persampelan yang dipilih ialah Pulau Redang, Port Dickson, Pulau Tioman dan Pulau Payar kerana dipengaruhi oleh Monsun Timur Laut dan Monsun Barat Daya serta kesan daripada Ayunan Selatan El Niño ke arah kawasan kajian. Serbuk sampel karang telah diambil pada selang 1 mm sepanjang teras yang kelihatan perubahan jalur karang dan dianalisis dengan menggunakan ICP-OES. Analisis regresi kuasa dua terkecil biasa menunjukkan bahawa nisbah Sr/Ca dalam teras dari semua tapak mempunyai hubungan negatif yang signifikan dengan suhu permukaan laut (SST). Pekali korelasi (r) adalah -0.704, -0.651, -0.667 dan -0.600 untuk Pulau Payar, Port Dickson, Pulau Tioman dan Pulau Redang. Nilai-nilai yang dipengaruhi oleh El Niño 2010 telah diplot antara jumlah Sr/Ca vs SST dan penurunan cerun regresi yang diperhatikan di teras karang Pulau Payar. Penentukuran Sr/Ca menggunakan persamaan kuasa dua terkecil linear menunjukkan bahawa nilai pintas (A) dan cerun (B) dari Pulau Tioman dan Port Dickson sangat serupa dengan hubungan Sr/Ca-SST yang dihasilkan daripada teras karang beresolusi tinggi dalam kajian lain.

Kata kunci: El Niño; karang; Sr/Ca; suhu; Semenanjung Malaysia

INTRODUCTION

The coral Sr/Ca-SST relationship is commonly estimated by linear regression of Sr/Ca against SST (Pfeiffer et al. 2006). Past SST reconstructions are then based on this calibration (Correge et al. 2004). Beck et al. (1997) found that increasing SST is related with decreasing Sr/Ca of the coral skeleton aragonite. On top of that, different calibrations have been found between studies from different sites where the average of several coral Sr/Ca calibrations suggests a temperature dependence of -0.062 mmol/mol°C^{-1} (Corrège 2006) and a more recent compilation shows a similar average slope (-0.047 ± 0.002 mmol/mol°C^{-1}) of the calibration equations (DeLong 2014). While Beck et al. (1992) were able to show a good correlation between Sr/Ca and SST. It was suggested that significant errors (1-2°C) could be caused by interspecific differences; variable calcification and extension rates; and variability in the Sr/Ca composition of seawater. In (1995), Villiers et al. then questioned the Sr/Ca based proxy by measuring three specimens of *Porites lobata* from Hawaii. All three samples grew at the same rate and the SST records were the same however their results showed three different trends in Sr/Ca, and consequently three distinctly different calibrations, with differences from the same reef as much as 2-3°C. Similar conclusions were found in different studies regarding growth rates on the Sr/Ca thermometer (Grove et al. 2013). Evidence of biological control on the uptake of Sr/Ca has been refuted subsequently by several studies. Shen et al. (1996) showed that species differences and growth rate variations did not appear to affect the Sr/Ca-SST relationship.

Looking at the connections between sites on the East and West coasts of Peninsular Malaysia, it was found that these two areas experience the monsoon seasons to varying different degrees. The East coast is more significantly affected by the Northeast Monsoon (NEM) season as opposed to the West coast (Suhaila et al. 2010). During the NEM, the exposed areas on the Eastern part of the Peninsula receive heavy rainfall and strong winds whereas areas which are sheltered by the mountain ranges are less affected. The period of the Southwest Monsoon (SWM) is drier in general, particularly for the states on the west coast of the Peninsula. In contrast, the two inter-monsoon seasons often result in heavy rainfall that usually occurs in the form of convective rains. During these seasons, the west coast is generally wetter than the east coast (Suhaila et al. 2010).

The combination of the abundance of coral reefs surrounding Peninsular Malaysia, different monsoon influences and warming caused by an El Niño event makes the study of corals in these areas essential in understanding how the Sr/Ca proxy responds. Ideally, a continuous time series of SST directly from the site where the coral grew should be used for Sr/Ca calibrations however, the limitation of local SST measurements has forced many studies to use SST data from satellites (Corrège 2006). Although *in situ* data is available from ships; research vessels; moored environmental buoys; drifting buoys; and near-surface measurements, the availability of data from certain locations are variable (Deser et al. 2010). There is no general agreement on which SST dataset should be used (Grove et al. 2013), therefore, for this study, the Reynolds et al. (2002) dataset, which is a combination of *in situ* and satellite SST, has been chosen. This study looks at the relationships of Sr/Ca, wind and SST between corals collected from the East and West coast of Peninsular Malaysia as well as determining whether there were any observable effects on Sr/Ca during the El Niño event that occurred in 2010.

MATERIALS AND METHODS

STUDY SITES

Coral core samples were collected from four sites around Peninsular Malaysia and the sampling locations are shown in Figure 1. In Pulau Payar, samples were collected from Pulau Payar Shark Point (6° 3’51.00”N 100° 2’33.00”E); Port Dickson, Tanjung Tuan (2°24’57.01”N 101°51’12.03”E); Pulau Redang, Kerengga Besar (5°45’15.00”N 103° 1’44.00”E); and Pulau Tioman, Tekek house reef (2°49’2.00”N 104° 9’6.00”E). Coral cores were collected from Pulau Payar in August 2015, Pulau Tioman in September 2015, Port Dickson in November 2015 and Pulau Redang in March 2016. A single core of 20-30 cm in diameter was collected from the vertical axis of each *Porites* spp. colony (2 colonies per site). The chosen boulder colonies measured 1 - 4 m in diameter, and were located at a depth of about 0.5 - 1 m below the low tide datum at each site following the same methods described by Scoffin et al. (1992). Coral cores were cut into 7 - 10 mm slabs along the vertical growth axis and linear extension rates were measured directly from banding seen in X-radiographs. Growth chronology and linear extension rates were resolved from the annual skeletal banding patterns as visualized in Figure 4 along the main vertical growth axis and at a resolution of 72 pixels cm^{-1}. Bioluminescence images of Pulau Payar and Pulau Tioman samples were also taken to complement the X-ray images.

ENVIRONMENTAL DATA

Monthly sea surface temperature data from 2008 - 2015 was obtained from the Reynolds et al. (2002) dataset. Meterological data (ambient temperature, rainfall and wind speed) was obtained from the Malaysian Meterological Department. Data was collected from the nearest available weather station i.e., Pulau Payar - Pulau Langkawi (6.333˚N 99.733˚E), Port Dickson - Chemara Res. Tanah Merah (2.645˚N 101.787˚E), Pulau Tioman - Mersing (2.450˚N 103.833˚E) and Pulau Redang - Kuala Terengganu (5.383˚N 103.100˚E).

GEOCHEMICAL ANALYSIS

The coral slices were washed with Milli-Q (18.2 MΩ, Millipore, USA) water in an ultrasonic cleaner for 10 min. This process was repeated 4-5 times until there was no visible residue from the coral slices and finally, the slices were dried in an oven at 60°C for > 24 h. Guided by the X-radiographs, a sampling path was selected for each coral slab along the apex of extending corallites visible along the coral slab surface (Figure 5). Linear extension growth rates were determined by alternating high and low density bands seen in X-ray images (Figure 5) that depict seasonal cycles (Knutson et al. 1972). Subsamples (powdered coral skeleton) for Sr/Ca analysis were extracted using a 0.8 µm engraving bit along the apex of extending corralites at 1 mm intervals. A Dremel 3000 variable speed rotary tool attached to a Dremel 220-01 drill press workstation was used for the extraction. Each sub-sample weighed between 140 and 250 µg and was dissolved in 1.5 mL 2% HNO_3. The samples were sent to Earth Observatory of Singapore, Nanyang Technological University to be analysed using an iCap 6000 series ICP-OES made by Thermo Electron Corporation. Coral Sr/Ca and time calibrations were conducted using the AnalySeries software (Paillard et al. 1996) followed by linear interpolation using Kaleida Graph (1997). The chronology of our coral Sr/Ca data was developed using anchor points (Charles 1997), which were fixed at the climatological SST maximum and minimum. A minimum of 4 anchor points per year were used which

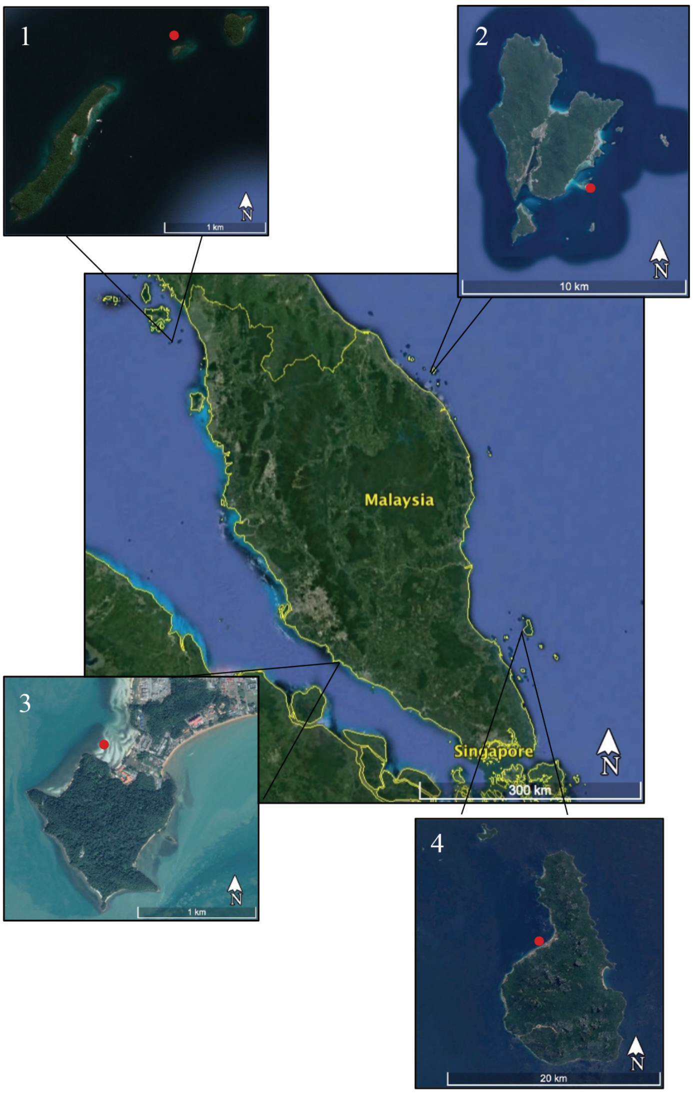

FIGURE 1. Satellite image of Malaysian Peninsular: 1. Pulau Payar, 2. Pulau Redang, 3. Port Dickson, 4. Pulau Tioman

were fixed to the SST max - min and inter monsoon seasons. Analysed data were assessed for accuracy and precision using a quality control protocol, which included reagent blanks, duplicate test, and certified geochemical standard reference material (JCp-1) with relative standard deviation < 1%. Matrix and drift effects were corrected using JCp-1 and internal laboratory standards.

RESULTS AND DISCUSSION

Sr/Ca AND SST

Two core samples were collected from the sampling sites, only one core from each site was used for the geochemical analysis. Both cores were examined and the core that showed a clear apex of extending corallites was chosen. The coral slab surfaces were also observed and the core with evidence extensive colonies of microborers was not chosen for geochemical analysis. The average value of JCp-1 was 8.83 ± 0.015 mmol/mol which was within the mean range reported in the interlaboratory study conducted by Hathorne et al. 2013 (8.54 to 8.98 mmol/mol). Mean Sr/Ca from the geochemical analysis were 8.79 ± 0.078 mmol/mol, 8.80 ± 0.056 mmol/mol, 8.78 ± 0.076 mmol/mol and 8.78 ± 0.040 mmol/mol for Pulau Payar ($n = 105$), Port Dickson ($n = 140$), Pulau Tioman ($n = 81$) and Pulau Redang ($n = 120$), respectively. Figure 2 shows the initial data obtained at 1 mm intervals prior to linear interpolation. Data obtained from ICP-OES analysis was compiled and linearly interpolated with satellite ERSST dataset with a data resolution of 1° × 1° grids by Reynolds et al. (2002). The chronology of our coral Sr/Ca data was developed using anchor points as suggested by Charles (1997), which were fixed at the climatological SST maximum and minimum. It was assumed that the measured Sr/Ca minimum corresponds to the seasonal SST maximum due to the inverse relationship between Sr/Ca and SST. Age assignments were determined using Analyseries (Paillard et

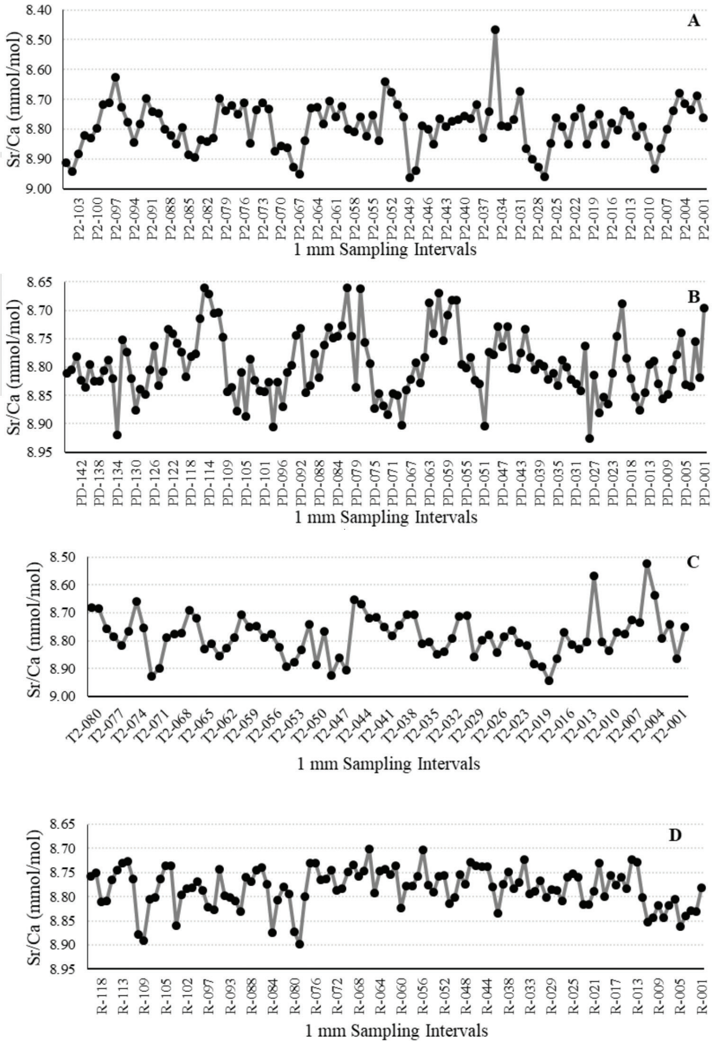

FIGURE 2. Graph of raw Sr/Ca (mmol mol^{-1}) data at every 1 mm sampling interval before age modelling for (A) Pulau Payar, (B) Port Dickson, (C) Pulau Tioman and (D) Pulau Redang

al. 1996) whereby Sr/Ca values were linearly interpolated between anchor points. Results from each site (Figure 3) showed a clear annual cyclicity pattern where the Sr/Ca minima occurs between December - February that appears to follow SSTs (Alibert & McCulloch 1997).

We also conducted an ordinary linear least squares regression using SPSS and obtained inverse relationships between Sr/Ca and SST. The calculated correlation coefficients (r) were -0.704, -0.651, -0.667 and -0.600 for Pulau Payar, Port Dickson, Pulau Tioman and Pulau Redang, respectively (Table 1). The relationship between SSTs and Sr/Ca at each site can be seen in Figure 3 whereby the cyclical pattern of the Sr/Ca changes are visible.

Table 2 shows the Sr/Ca values from this study compared to previous other studies coupled with SST ranges. Sr/Ca concentrations from this study are similar to values from studies conducted in other regions with similar climates (Deng et al. 2014). In Table 2, we can observe the Sr/Ca ranges recorded in previous studies as

TABLE 1. Correlation coefficients, n and p-values of Sr/Ca vs SST at all four locations from Ordinary Linear Least Squares Regression analysis

Location	n (# of pairs)	Sr/Ca vs SST correlation coefficients	p-value
Pulau Payar	72	-0.704	0.05
Port Dickson	81	-0.651	0.01
Pulau Tioman	77	-0.667	0.01
Pulau Redang	78	-0.600	0.01

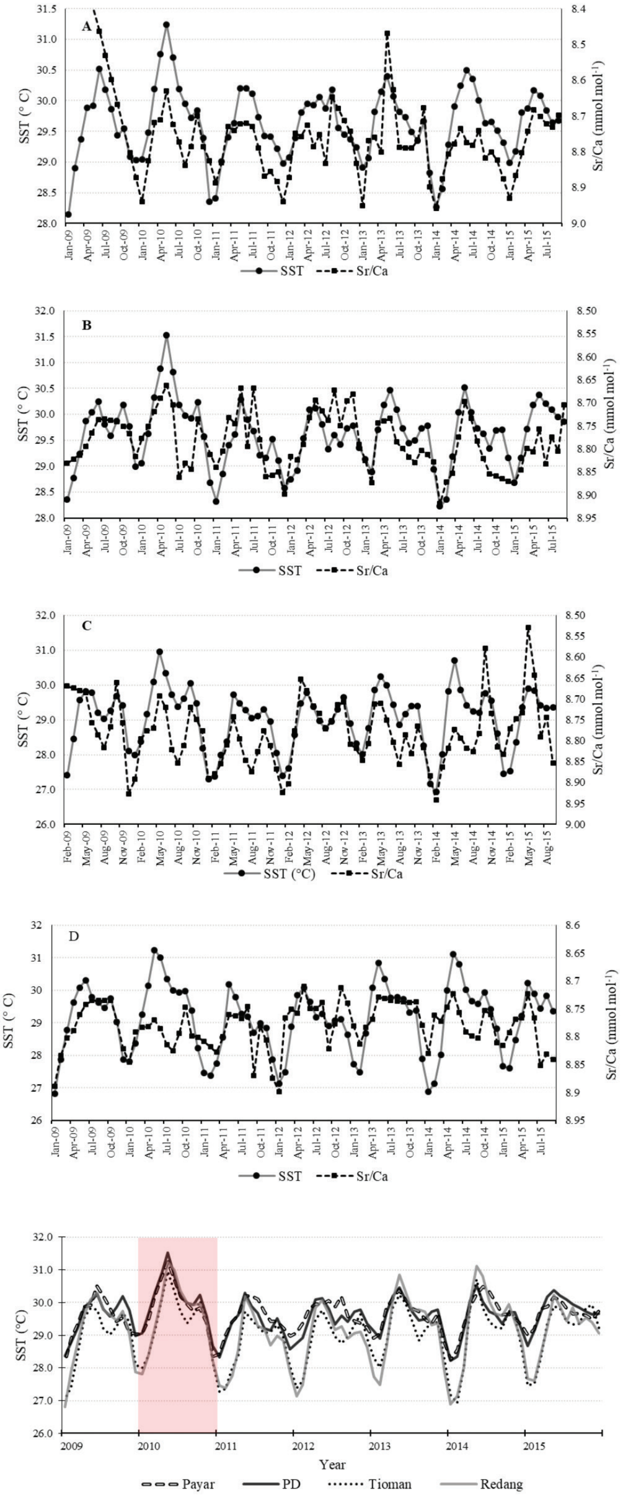

FIGURE 3. Monthly average SST from Pulau Payar (99.5E 5.5N), Port Dickson (2.5N 101.5E), Pulau Tioman (2.5N 104.5E) and Pulau Redang (6.5N 102.5E) from 2009 until 2015 (Reynolds et al. 2002). Panel shaded in red shows SSTs in 2010

well as from seawater samples collected in the Atlantic and Pacific Oceans. It has been shown that the Sr/Ca ranges in seawater do not fluctuate significantly regardless of the temperature (Villiers 1999) but the concentrations in the coral skeleton vary due to the effects of temperature on Sr^{2+} uptake.

Sr^{2+} is chemically similar to calcium (Ca^{2+}) and is generally considered to substitute for Ca^{2+} in the aragonite lattice (Speer 1983) of biogenic carbonate (coral skeletons, mollusc shells, foraminifera and fish bones). A study conducted in the Great Barrier Reef by Marshall and McCulloch (2002) recorded a difference of 0.40 mmol/mol

TABLE 2. Sr/Ca and SST values from this study and published studies

Site	Sample type	Sr/Ca Range (mmol mol^{-1})	Mean Sr/Ca (mmol mol^{-1})	Temperature (℃)
Pulau Payar	*Porites* sp.	8.47 - 8.96	8.79 ± 0.078	28.2 - 31.2
Port Dickson	*Porites* sp.	8.66 - 8.92	8.80 ± 0.056	28.2 - 31.5
Pulau Tioman	*Porites* sp.	8.53 - 8.94	8.78 ± 0.076	26.9 - 31.0
Pulau Redang	*Porites* sp.	8.71 - 8.90	8.78 ± 0.040	26.8 - 31.2
Atlantic and Pacific Ocean (Villiers 1999)	Seawater	8.49 - 8.61	8.54 ± 0.038	6.8 - 30.1
Great Barrier Reef (Marshall & McCulloch 2002)	*Porites* sp.	8.68 - 9.08	n.a.	30.4 - 22.7
	Porites sp.	8.63 - 9.08	n.a.	n.a.
Persian Gulf (Gischler et al. 2005)	*Porites lutea*	8.80 - 9.60	n.a.	16.0 - 34.0
Tahiti (Cahyarini et al. 2009)	*Porites* sp.	8.51 - 8.84	n.a.	25.7 - 28.9
	Porites sp.	8.85 - 8.97	n.a.	25.7 - 28.1
Southwestern South China Sea (Mitsuguchi et al. 2008)	*Porites* sp.	8.70 - 9.11	n.a.	~ 25.0 - 31.0
Northern South China Sea (Chen et al. 2013)	*Porites lutea*	8.99 - 9.67	n.a.	13.0 - 30.0
Great Barrier Reef (Deng et al. 2014)	*Porites* sp.	n.a.	8.86 ± 0.038	~ 25.6 - 27.6
	Porites sp.	n.a.	9.03 ± 0.042	~ 25.6 - 27.7

between its highest and lowest value. In Tahiti, Cahyarini et al. (2009) recorded a difference of 0.33 mmol/mol and 0.12 mmol/mol between the highest and lowest values of two different coral cores.

In order to improve the correlation between monthly coral Sr/Ca and SST, it has been proposed to average Sr/Ca measurements from multiple coral colonies taken from different locations in a given region. It is believed that SST reconstructions from average proxy records are more representative of regional SST variations (Cahyarini et al. 2009) as compared to single core measurements. Apart from that, better correlation coefficients can be obtained by increasing the length of the cores sampled in order to represent >50 years of geochemical data.

EFFECTS OF ENSO AND LINEAR EXTENSION ON THE Sr/Ca THERMOMETER

From 2009 until 2015, the yearly SST fluctuations have similar cycles (Figure 4). However, there is a spike in SSTs in May and June of 2010 which coincides with the moderate El Niño Southern Oscillation (ENSO). A large-scale oceanic warming event in the tropical Pacific Ocean that occurs every few years is commonly termed the El Niño event. It is characterized by an inter-annual seesaw in tropical sea level pressure between the western and eastern Pacific, consisting of a weakening and strengthening of the easterly trade winds over the tropical Pacific (Wang et al. 2017).

Although there is an increase in SSTs at all sites in May and June of 2010, these observations were not reflected in coral Sr/Ca (Figure 3). A sharp decrease in Sr/Ca was expected at all sites during that time, however, none was observed. Ferrier-Pagès et al. (2002) noted that the rate of calcification should be taken into account when measuring Sr/Ca because they found an inverse relationship between the rate of Sr^{2+} incorporation and calcification rates. In this study, we measured the linear extension rates directly from the X-ray images (Figure 5). The yearly extension rates are shown in Figure 6 and showed a slight decline in the Port Dickson and Pulau Payar core in 2010 compared to the years before (2009) and after (2011). The linear extension rate in 2010 for the Pulau Redang core showed a more prominent decline compared to the other sites. A decline this evident may have been caused by the El Niño event which in turn may have contributed to the lack of decrease in Sr/Ca.

Recent work by Tanzil et al. (2009) on the growth of massive *Porites* spp. demonstrated a decrease in calcification rate coincident with an increase in SST over the same period. They also found that there was a decrease in calcification rate by ~ 21% between 1988 and 2003 in Great

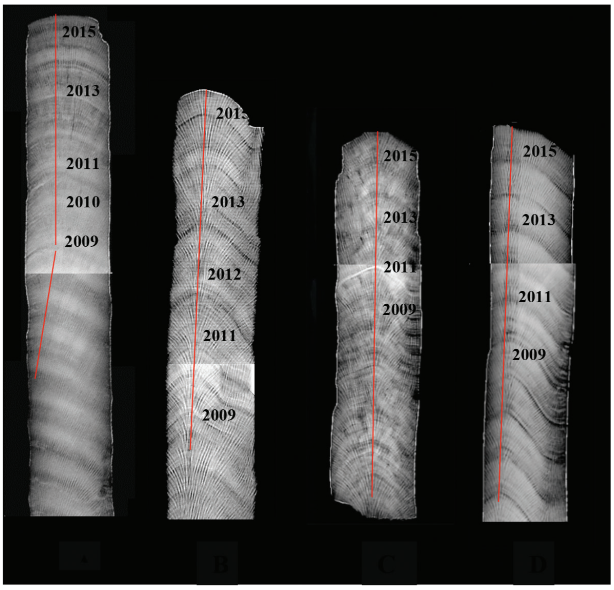

FIGURE 4. X-radiograph images of coral cores; (A) Pulau Payar, (B) Port Dickson, (C) Pulau Tioman and (D) Pulau Redang. Years and sampling path (red line) are indicated

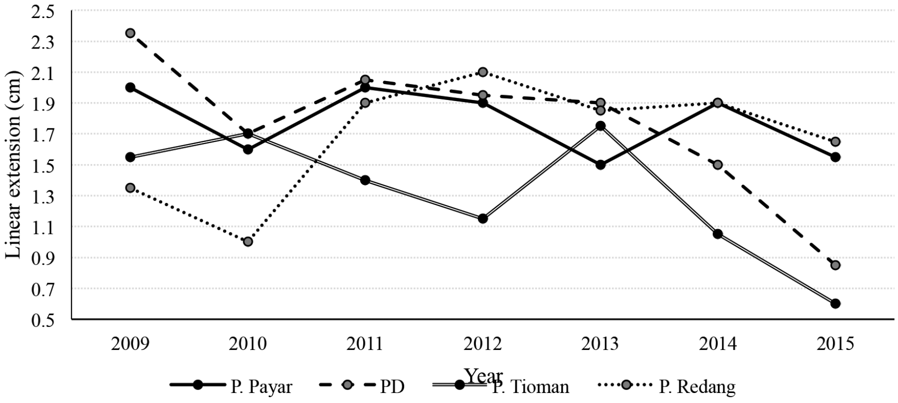

FIGURE 5. Linear extension rates in corals from all four sites from 2009 until 2015

Barrier Reef whereas there was a decline of 19.4 to 23.4% in corals from the Andaman Sea, Thailand. An even more recent study conducted by Tortolero-Langarica (2016) on free living coral *Porites lobata* found a decrease in linear extension and calcification rates during the 2009-2010 period and attributed the decrease to the El Niño event. Tortolero-Langarica et al. (2017) also reported similar results in a study on growth rates of the reef-building corals *Pavona gigantea* and *Porites panamensis* from the northeastern tropical Pacific. Their long-term analysis showed that annual periods with records of abnormal temperatures (coinciding with moderate and severe El Niño and La Niña periods), resulted in the lowest values in annual extension, density and calcification rates.

Apart from the effects of calcification on the coral Sr/Ca, the incorporation of trace elements in the aragonite crystals ($CaCO_3$) are also subject to varying levels of physiological control. Corals precipitate their skeleton from a partially isolated calcifying fluid (McCulloch et al. 2012). This calcifying fluid is partially isolated from the ambient seawater and then modified, potentially affecting how trace elements are incorporated into the coral

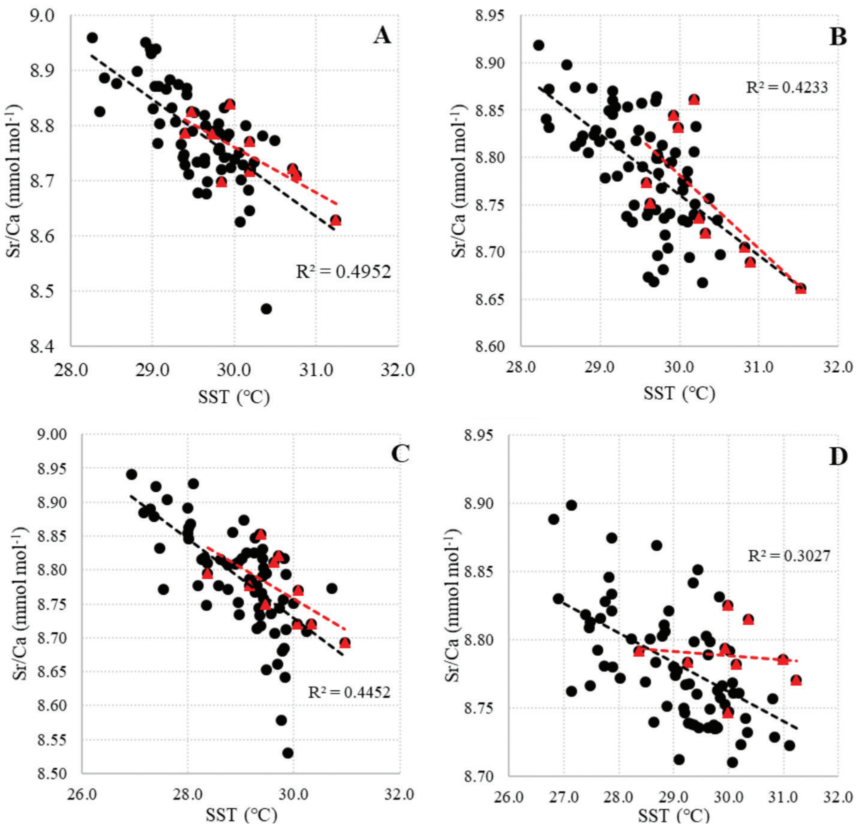

FIGURE 6. Relationships between SST and Sr/Ca in samples collected from A) Pulau Payar, B) Port Dickson, C) Pulau Tioman and D) Pulau Redang. Values obtained during the ENSO event are plotted in red with the respective red trendlines

skeleton *via* 'vital-effects' (Allison & Finch 2007). Current knowledge about the role of coral 'vital effects' have been largely limited to inferences based on comparisons between the geochemical composition of aragonite in coral skeletons collected *in situ* and laboratory inorganic experiments (Cohen & Gaetani 2010). Consequently, the significance of 'vital effects' on longterm geochemical proxy records is poorly understood.

With reference to a recent study conducted by Clarke et al. (2017), we extrapolated the Sr/Ca - SST values during the El Niño event (February 2010 to November 2010) to analyze the effects of thermal stress on the Sr/Ca temperature proxies. We calculated short-term Sr/Ca – SST correlations that corresponded with the timing of the 2010 El Niño in Peninsular Malaysia. The short-term correlations can be seen in Figure 7 and are plotted in red. Based on Figure 7, the Sr/Ca-SST linear regressions during El Niño at Pulau Payar, Port Dickson and Pulau Tioman produced similar results to the rest of a study period. Only minor differences were observed in the slope, intercept and r^2 values of the linear regressions in both bulk and El Niño Sr/Ca-SST correlations at these three study sites (Table 3).

When we observed Figure 7(D), there was a decline in slope and r^2 values observed during the short-term El Niño period. Based on Figure 7, Pulau Redang showed the lowest correlation in the Sr/Ca – SST linear regression. This discovery of the lower slope and r^2 values seem to indicate that this particular coral colony may have been affected by thermal stress induced physicochemical disturbances. This is further supported by the findings that the slope and r^2 values return to pre-thermal stress levels after the El Niño event. In the study conducted by Clarke et al. (2017) they found a short-term decline in the slope of the Sr/Ca-SST regression compared to the pre-thermal stress values. Similarly, they also recorded an abrupt decline in the linear extension rate, accompanied by a thin, high-density band, typically indicative of environmental stress (Lough & Cooper 2011) that was evident in the X-ray image of the core. These findings are notably similar to the findings in the Pulau Redang core in this study.

Table 3 shows the sample size (n), slope (B), intercept (A), coefficient of determination (r^2) and p-values of the linear regressions between bulk samples and El Niño subsamples from all sites. As seen in the table, the r^2 value of the El Niño subsample from Pulau Redang is only 0.021 and p-value is 0.69 which means it is statistically insignificant. However, the bulk linear regression in Pulau Redang is statistically significant with an r^2 value of 0.360.

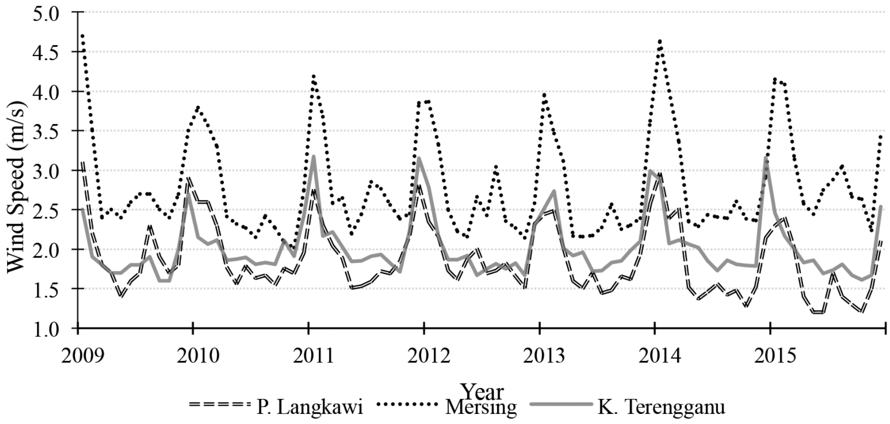

FIGURE 7. Monthly average wind speed (m/s) from all meteorological stations except Port Dickson: P. Langkawi (Pulau Payar), Mersing (Pulau Tioman) and K. Terengganu (Pulau Redang)

TABLE 3. Linear regression with ordinary least squares from core samples from all sites. Linear regressions of the entire study period are shown in the Bulk values whereas the El Niño event values are the linear regressions from February 2010 until November 2010

Site	Period	Sr/Ca				
		n	Slope (B)	Intercept (A)	r^2	p
Pulau Payar	Bulk	72	-0.106	11.921	0.495	<0.001
	El Niño	10	-0.083	11.256	0.597	<0.01
Port Dickson	Bulk	81	-0.064	10.683	0.423	<0.001
	El Niño	10	-0.078	11.122	0.478	<0.05
Pulau Tioman	Bulk	77	-0.059	10.485	0.446	<0.001
	El Niño	10	-0.046	10.150	0.342	<0.05
Pulau Redang	Bulk	78	-0.023	9.436	0.360	<0.001
	El Niño	10	-0.004	8.903	0.021	<0.7

This shows that the El Niño subsample does not follow the same regression model compared to the rest of the study period. When linear regression was conducted on subsamples before and after the El Niño event, the r^2, B and A values did not change drastically and the p-value was <0.001. These results were only found in the Pulau Redang core which strongly suggests that the increased temperature may have had an effect on role in this particular colony during the El Niño thermal stress event.

Theoretically, when temperature increases, Sr/Ca in the coral skeleton should decrease. However, this was not what happened in the Pulau Redang core sample (Figure 3). The irregular Sr/Ca values were coupled with a decline in linear extension rates. These two factors provide additional indication that the Pulau Redang core was impacted by thermal stress during the 2010 El Niño event. This increase in Sr/Ca is consistent with previous research that suggested the ability of *Porites* sp. to pump calcium from the ambient seawater into the calcifying fluid *via* the Ca^{2+} ATPase transport enzyme can become impaired during periods of thermal stress (D'Olivo 2017). It is also possible that a reduction in calcium pumping could occur due to reduction in the supply of the energy needed to drive the molecular pump (Fang et al. 1991). When coral bleaching occurs, the symbiotic algae are expelled by the host polyp due to the high temperatures. Given that symbiotic algae provide the principle source of energy supporting calcification by the coral host, some reduction in the supply of metabolic energy (in the form of ATP) to the coral host during periods of thermal stress could be expected (Clarke et al. 2017).

Interestingly, we observed that the decline in slope of the Sr/Ca-SST calibration for the Pulau Redang coral during the 2010 thermal stress event (82.6%) was similar to the differences in slopes observed between day and night time skeletal deposits (~80%) for *Porites lutea* (Clarke et al. 2017). The reduction in the slope of the Sr/Ca-SST regression could suggest that the chemical conditions of the calcifying fluid of the Pulau Redang coral during the 2010 warming event were more similar to that of night time due to the lack of energy provided by the symbiotic algae. This idea is further supported by the decline in linear extension and hence calcification (Clarke et al. 2017).

CORAL LINEAR EXTENSION AT ALL SITES

According to Figure 6, there are declines in linear extension rates for samples from Pulau Payar, Port Dickson and Pulau Redang in 2010. This decline could be a result of high SSTs recorded due to the El Niño event or they could merely be a result of individual colony growth changes. No such decline is evident in the Pulau Tioman core. Observing the growth rates from all the cores, some years showed that the linear extension fluctuations were above 0.6 cm/year. This extension rate is the threshold for growth-related effects in *Porites* sp. A lot of factors may affect the linear extension rates for these core samples such as light availability, skeletal density, distance from shore and average SSTs (Lough & Barnes 2000). The very low extensions in all cores measured in 2015 could be due to the coral colonies being cored before they were able to complete their yearly growth cycle. Density banding patterns in corals from the East and West Coast occur at different times of the year. For West coast *Porites* sp., high-density bands were found to occur between May and September. However, on the East Coast, high density bands are deposited between November and February (Tanzil et al. 2013).

There is a slight difference between the trend of linear extension rates in the cores from Pulau Payar and Port Dickson. No significant correlation was found however, thus the similarities could be coincidental. On average, the highest linear extension was seen in the Pulau Payar core (1.78 cm/year) and the lowest was in the Pulau Tioman core (1.31 cm/year). It has been found that the cores collected from the East coast of Peninsular Malaysia have higher skeletal bulk density values compared to cores from the West coast. Tanzil et al. (2013) found that the skeletal bulk density on the East coast averaged 1.2 - 1.3 g cm^{-3} whereas cores on the West coast averaged below 1.2 g cm^{-3}. Extension rate in massive *Porites* sp. is inversely related to average skeletal density (Lough & Barnes 2000). One explanation for the higher densities found in the East coast coral is the yearly prevalence of the NEM that causes the eastern part of the Peninsular Malaysia to receive heavy rainfall and strong winds. We can see the significantly higher wind speeds recorded in Pulau Tioman in Figure 8. This has been shown in the findings of Scoffin et al. (1992) where average density increased and extension rate decreased along an environmental gradient of increasing hydraulic energy. In 2016, Tanzil et al. studied coral cores from the Thai-Malay Peninsula and summarised that the high density banding occurs in ~Nov/Dec at East Coast locations whereas at West Coast locations the high density bands are deposited in ~May/June. These are predominantly the times where the Northeast Monsoon and Southwest Monsoon occur at each respective coast which results in higher wind speeds. Evidence of the connection between wind speed and average coral density was also found in a study by Charuchinda and Hylleberg (1984) where they concluded that skeletons of *Acropora aspera* in more exposed environments were denser. Similarly, increased water movement is beneficial to corals by removing sediment, flushing waste, reducing salinity and enhancing the diffusion of nutrients by reducing the thickness of the diffusion boundary layer around the coral (Todd 2008).

Sr/Ca RELATIONSHIPS BASED ON LOCATIONS

The relationship between Sr/Ca from samples collected on the East and West coast was analysed to determine whether location of reefs influenced Sr/Ca. Due to the different monsoonal effects on both East and West coast, e.g. Southwest Monsoon and Northeast Monsoon, this may have had an effect on the Sr/Ca thermometer. It was observed that there were weak to moderate relationships between Sr/Ca fluctuations based on location. Firstly, we looked at any connections between sites on the East

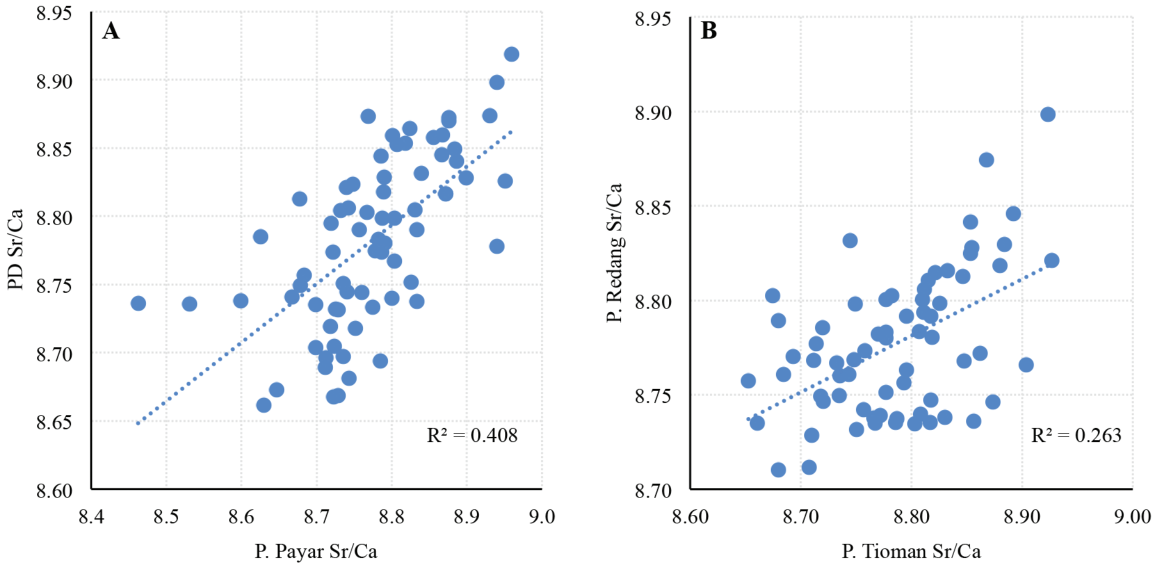

FIGURE 8. Relationships between Sr/Ca (mmol/mol) in coral samples from the East coast (A) and West Coast (B) of Peninsular Malaysia

and West coasts of Peninsular Malaysia. These two areas experience the monsoon seasons to varying different degrees. The East coast is more significantly affected by the NEM season as opposed to the West Coast. During the NEM, the exposed areas on the eastern part of the Peninsula receives heavy rainfall and strong winds whereas areas which are sheltered by the mountain ranges are less affected. The period of the SWM is drier in general, particularly for the states on the west coast of the Peninsula. In contrast, the two inter-monsoon seasons often result in heavy rainfall that usually occurs in the form of convective rains. During these seasons, the West Coast is generally wetter than the East Coast (Suhaila et al. 2010).

Based on the correlation coefficients, the relationship was stronger between the samples collected on the West compared to the East Coast. The r^2 values for the West Coast were 0.408 whereas they were 0.263 for the East Coast samples (Figure 9). The different r^2 values obtained could be due to the different intensities of seasons experienced by the different coasts. The samples collected from the West Coast are situated in the Malacca straits that experiences considerably lower average wind speeds (Figure 8), thus, this contributes to a higher average yearly SST (Figure 4). Lower effects of the NEM on the West Coast also influence the water surrounding the reef sites and produce a less turbulent environment. A more stable climate coupled with more uniform water movement could be one of the reasons why the relationship between West coast samples are higher. In addition, we can see from Figure 8, that there is a very significant difference between wind speeds from the two sites on the East Coast. The yearly average wind speeds in Kuala Terengganu ranged from 1.9 - 2.2 m/s,

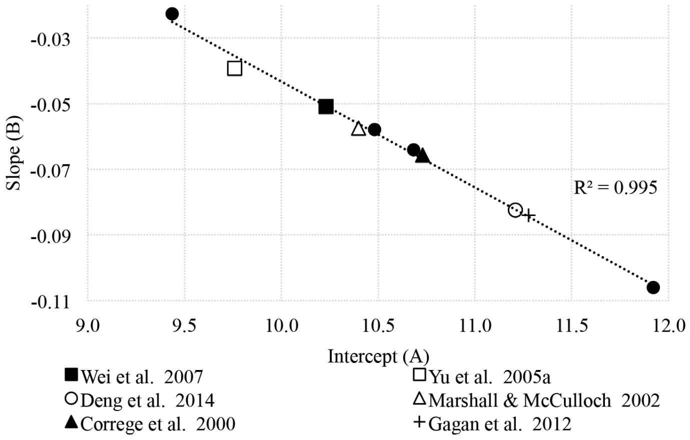

FIGURE 9. Plot of slope (B) against intercept (A) for the selected Sr/Ca-SST calibrations. Sr/Ca-SST calibrations are expressed as Sr/Ca = A B SST. The solid circle indicates monthly resolved calibration of the *Porites* sp. coral from study

however, they were much higher in Mersing and ranged from 2.6 - 3.0 m/s which may have contributed to the differences in r^2 values.

According to correlation analysis of the East and West Coast SSTs, it was found that the relationship was higher on the East (r^2 =0.907) than West Coast (r^2=0.803). Theoretically this should mean that the Sr/Ca relationship between samples from the East Coast should be higher, however we must take into account the r^2 values between Sr/Ca and SST at each individual site. We found that the Sr/Ca and SST relationship from the Pulau Redang core (Figure 7) was the lowest amongst all samples collected (r^2 = 0.302). Such differences could be due to non-climactic factors of vital effects which may have affected the fidelity of the coral core (Lough 2004) as we discussed in the previous subsection. The dramatically reduced r^2 values that were obtained as a result of the ENSO warming period in 2010 affected the bulk r^2 values and incresed the Sr/Ca ratios during the same period. This will have had a significant effect on the correlations between the Sr/Ca values from the two East coast cores. This is due to the Pulau Tioman core being relatively unaffected by the ENSO warming event whereas the Pulau Rendang core was drastically affected.

The decline in linear extensions in 2010, which may have been caused by the changes such as vital effects could have also contributed to the lower R^2 value. Factors such as reduced colony health, coral bleaching followed by recovery and skeletal destruction by grazers could have caused the resulting lower correlations between both SST-Sr/Ca in Pulau Redang and Sr/Ca in the East Coast even though SST conditions they experienced were almost the same (Jones et al. 2009). Based on a study conducted by Lee and Mohamed (2011), the sedimentation rates in Pulau Redang are much lower compared to Pulau Tioman. They also stated that the organic content in the sediment is quite high which helps contribute to the feeding activities of *Porites* sp. These conditions show that Pulau Redang is the ideal location for the healthy growth of *Porites* sp., thus, rules out any significant difference in environmental conditions.

This leaves us to conclude that the particular colony that was cored had been compromised by physical disturbances. Prior to geochemical analysis, there were no observable traits that suggested the Pulau Redang core had been compromised and thus these findings were only found after Sr/Ca values were obtained. In order to reduce these effects, replication from different coral colonies is very important as suggested and demonstrated in several recent studies (Zinke et al. 2014). Ideally, at least 2-3 coral cores from a reef location are necessary because coral records extracted from a single coral colony cannot be used to distinguish between climate signals and biologically induced noise (Deng et al. 2014). Unfortunately, due to time and logistical constraints throughout this study, only 2 cores were collected per site and geochemical analysis was only conducted on the core that had no marks left by microborers and visible extending corallites.

Sr/Ca CALIBRATION

The ratios between Sr and Ca were measured and compared to SSTs. When we conducted a linear least squares regression between Sr/Ca ratios with the monthly SSTs, significant negative correlations were found. These results are expected due to the inverse relationship between Sr/Ca and SSTs. Subsequently, the calculated correlation coefficients (r) were -0.704, -0.651, -0.667 and -0.600 for Pulau Payar, Port Dickson, Pulau Tioman and Pulau Redang, respectively. Scatter plots of SST vs Sr/Ca from all sites are shown in Figure 7. Based on the r values, the strongest relationship between SST and Sr/Ca was found in the coral from Pulau Payar. The relationship between Sr/Ca and SST obtained by a linear least squares regression is shown Table 1.

Referring to Table 4, the intercept (A) and slope (B) values from Pulau Tioman and Port Dickson are very similar to the previous Sr/Ca-SST relationships generated from high resolution coral series in which the values generally range from 9.760 to 10.956, and from -0.0393 to -0.0795 for A and B, respectively (Wei et al. 2007). The A and B values from Pulau Payar and Pulau Redang did not fall within these acceptable ranges (Table 4). This could be due to the multiple different factors such as calcification rate and other biological controls. Villiers et al. (1995) suggested temperature is not the only important control on coralline Sr/Ca ratios. In particular, they suggested that precipitation rate (affecting Sr/Ca concentrations in seawater) or other biological processes also may be important (calcification rate, linear extension rate).

Equally important, all of the temperature proxies require the oceanic concentration ratio of Sr/Ca to be unchanged. Measurements of Sr/Ca in seawater for modern oligotrophic reef settings in the Pacific and Atlantic Oceans indicate seawater Sr/Ca ratios are not as stable as once supposed, but exhibit a range of 8.51 to 8.55 mmol/mol (Shen et al. 1996; Villiers et al. 1994). These two main factors (precipitation and biological factors) could have been the causes of the variations in the calibration equations for the Pulau Payar and Pulau Redang cores. Terrestrial influences towards the coastal areas where these samples were collected could have also played a part in the varying Sr/Ca values obtained. Higher or lower concentrations of Sr^{2+} from terrigenous sources in the North could have influenced Sr^{2+} concentrations in seawater. A study by Ong et al. (2015) found metal concentrations in the sediment of Pulau Bidong (close to Pulau Redang) is mainly influenced by natural processes. They indicated that the trace metals occurred in both lithogenous and non-lithogenous fractions and thus, there was minimal anthropogenic influence of heavy metals in surface sediment surrounding Pulau Bidong of Terengganu.

On the other hand, Pulau Payar is located 30 km South of Pulau Langkawi on the West coast of Peninsular Malaysia. Lee and Mohamed (2009) conducted a study

TABLE 4. Summary of all the Sr/Ca vs. SST calibrations published to date using the genus *Porites*

Publication	A	B	Method
Wei et al. 2007	10.23	-0.05084	TIMS/ICP-AES
Yu et al. 2005	9.76	-0.0393	TIMS/ICP-AES
Deng et al. 2014	11.209	-0.0824	ICP-AES
Marshall & McCulloch 2002	10.4	-0.0575	TIMS
Corrège et al. 2004	10.73	-0.06567	ICP-MS
Gagan et al. 2012	11.278	-0.084	TIMS
Pulua Tioman	10.482	-0.058	ICP-MS
Pulau Redang	9.4361	-0.0226	ICP-MS
Pulau Payar	11.921	-0.106	ICP-MS
Port Dickson	10.683	-0.0641	ICP-MS

on *Porites* sp. collected from Pulau Langkawi found high pH readings due to the erosion of limestone ($CaCO_3$). The elevated pH in this region could affect the incorporation of Sr in to the coral skeleton may have influenced the intercept (A) and slope (B) values in the Pulau Payar core. Pulau Langkawi coastal region is also impacted by high sedimentation rates. It is noted that millions of tons of sediment particles are transported annually by major rivers of the east coast of Sumatra and the west coast of Peninsular Malaysia to the coastal water of the Malacca Straits (Soegiarto 2000).

Despite these differences, a good linear regression line can be obtained when plotting A against B of the thermometer by monthly calibrations compiled from previous studies (Figure 9). This method was suggested by Marshall and McCulloch (2002) to check the validity of Sr/Ca-SST calibration and was based on the hypothesis that corals from different localities respond to their own particular environment, or that certain types of environments exert a control on coral physiology. Therefore, the exceptional linear relationship shown in Figure 9 suggests that the monthly calibration of Sr/Ca–SST from this study shows that the Sr/Ca series can be used as a reliable proxy for SST in Peninsular Malaysia.

CONCLUSION

Linear least squares regression showed a significant negative correlation between Sr/Ca ratios and satellite sea surface temperature. Correlation coefficients (r) were -0.704, -0.651, -0.667 and -0.600 for Pulau Payar, Port Dickson, Pulau Tioman and Pulau Redang, respectively. A significant decline in the regression slope during the El Niño event was evident especially in the Pulau Redang coral core. The El Niño subsample did not follow the same regression model compared to the rest of the study period which indicated temperature related effects on the incorporation of Sr^{2+} into the coral skeleton. Finally, Sr/Ca – SST calibrations showed similar relationships in all the coral series with previous studies around the world indicating that coral samples from Peninsular Malaysia are ideal for future paleoclimate and geochemical studies.

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